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HYDROELECTRIC DEVELOPMENTS IN THE SCOTTISH HIGHLANDS

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SYNOPSIS

The monster of Loch Ness and the scenic beauty of Loch Lomond in Scotland are internationally renowned but for an engineer even far greater attractions exist, namely, the various hydro-electric projects. From a modest beginning in 1943, the North of Scotland Hydro-Electric Board (NSEB) achieved dramatic progress in power generation.

Although many types of dams have been constructed, buttress types are predominant mainly because of foundation and site conditions. Nearly every type of buttress dam has been built: Gravity head at Sloy; round head at Shira; and diamond head at Errochty. The latest improved designs are more simplified and, hence, easier to construct. Heads ranging from 1,362 ft at Finlairg to approximately 18 ft at Morar have been developed. The Cruachan pumped storage plant has one of the largest reversible pump turbine in the world.

The growth of hydroelectric development in the Scottish Highlands is traced and interesting aspects of certain schemes are described, notably that of Glen Shira, Allt-na-Lairige, and Cruachan. Contributions of power to stop the gradual dwindling of population are examined together with economic development.

INTRODUCTION

The northern part of Great Britain is known as Scotland and has a total of nearly 30,000 sq miles, with a maximum length of approximately 320 miles and breadth of 150 miles. Bonnie Scotland is a picturesque country and the

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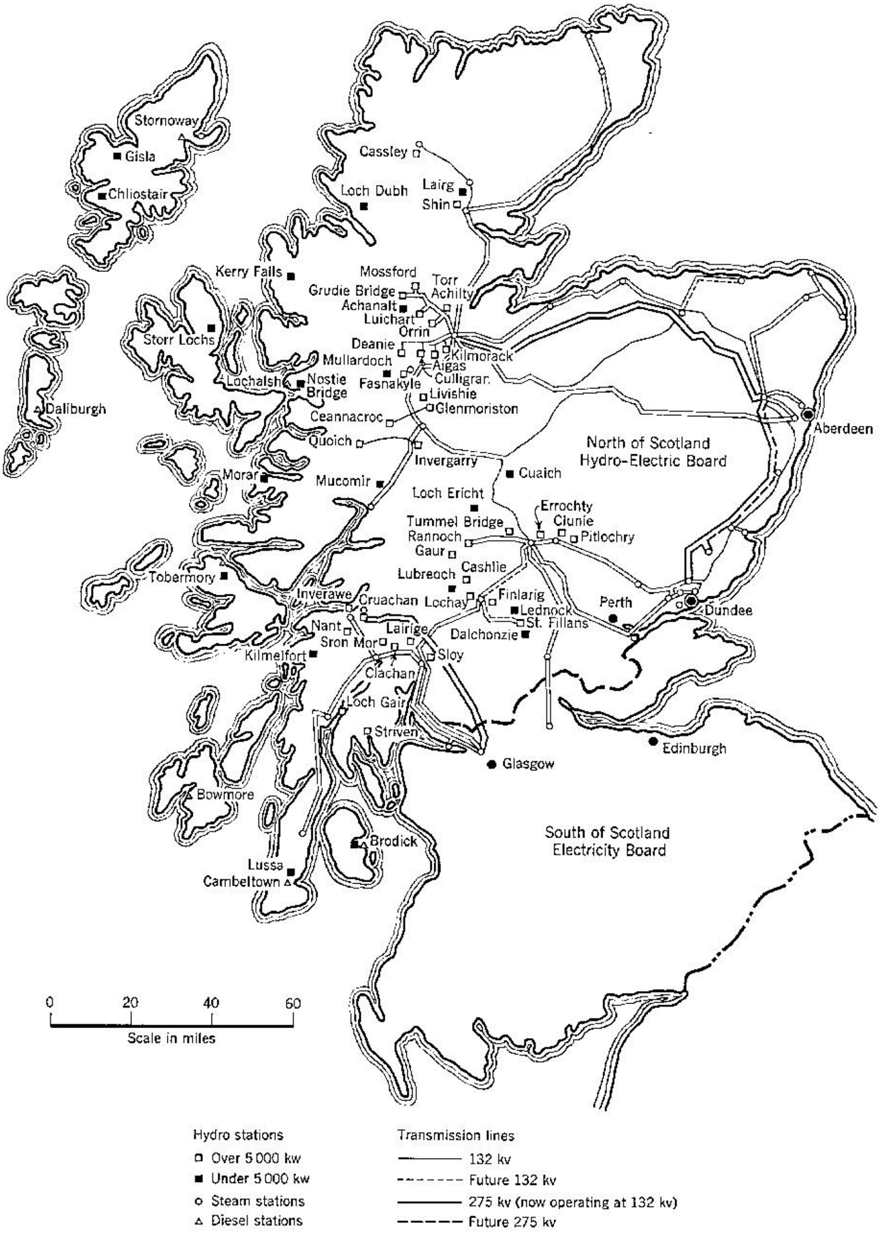

FIG. 1.—MAP OF SCOTLAND AND LOCATION OF SOME SCHEMES

English have been baffled by both her natives and language from time immemorial.

Insofar as generation of power is concerned, the country is divided in two parts and served by the South and North of Scotland Hydro-Electric Boards. Most of the dams of England are designed primarily for water supply, whereas in Scotland the emphasis is on hydroelectric power generation. The growth of power since 1950 has been phenomenal and practically all the hydroelectric schemes of Great Britain are concentrated in the Scottish Highlands and come under the jurisdiction of the NSEB. Locations of some of the schemes are shown in Fig. 1. The Scottish engineers are handicapped by the fact that neither large river systems nor high heads are available, but what they have achieved already and are planning to do are a great credit to them. The data for the ten highest dams built by the NSEB are given in Table 1.

The Highlands account for three quarters of the total area of Scotland and nearly one-fourth the area of Great Britain. As a result of constant migration to the more industrialized parts of Scotland and England, the population of the Highlands has constantly dwindled over the past two centuries and is now only a quarter of the population of Scotland. The main industries of the Highlands are agriculture, fisheries, and recently, tourism. Poor quality of soil and high rainfall do not make agriculture profitable.

TABLE 1.—TEN HIGHEST DAMS BUILT BY THE NSEB

Dam	River	Type	Height above ground level, in feet
Sloy	Inveruglas Water	Buttress	177
Orrin	Orrin	Gravity	146
Cruachan[a]	Cruachan	Buttress	143
Errochty	Errochty	Buttress	136
Shira	Shira	Buttress	127
Quoich	Gearr Garry	Rockfill	126
Lawers	Allt a Mhoirneas	Buttress	126
Mullardoch	Cannich	Gravity	119
Cluanie	Moriston	Gravity	114
Benevean	Affric	Gravity	112

[a] Under construction

Countless lochs and small islands scattered throughout the length and breadth of the country make transmission of power a difficult and costly problem. In addition, in some cases, the scatter of consumers over a wide area makes supply of electricity an uneconomic proposition and no doubt it must be subsidized by more highly populated areas. It is estimated that in 1963 the supply of electricity to remote areas resulted in the substantial loss, to the NSEB, of £2,000,000 ($5,600,000), which had to be met from other sales of electricity.

Table 2 shows the output of some of the hydroelectric stations of the NSEB.

RAINFALL AND CLIMATE

The climate is generally mild and is conducive to development of water power. The Gulf Stream on the west coast has a considerable bearing on the temperature as well as rainfall. Mild temperature and high humidity do not make evaporation much of a problem. In fact, evaporation is generally constant over the years and practically occurs during the seven summer months. The rainfall is unpredictable and amounts as high as 216 in. per yr have been recorded. The annual average rainfall varies from approximately 30 in. in the East coast to 120 in. and more in the West. The NSEB has 225 rain gages,[2] besides the reading available from the Metropolitan Office. The rainfall varies from approximately 150% of the long term average in a wet year to 70% in a dry year.

TABLE 2.—OUTPUT OF SOME HYDROELECTRIC STATIONS

Station	Gross head, in feet	Plant capacity, in kilowatts	Annual output, in million units
Clachan	965	40,000	74
Clunie	173	61,200	165
Errochty	610	75,000	84
Fasnakyle	522	66,000	223
Finlarig	1,362	30,000	80
Lochay	592	47,000	160
Morar	18	750	3
Orrin	728	18,000	76
Rannoch	512	48,000	174
Sloy	910	130,000	120
Tummel	173	34,000	120

BRIEF HISTORY OF HYDROELECTRIC POWER DEVELOPMENT

Most of the hydroelectric power generated for industrial use in Scotland before the NSEB was established in 1943 was exclusively for the use of the British Aluminium Company. Three generating stations at Foyers, Kinlochleven, and Fort William[3] produced an aggregate of 111,000 kw of direct current energy and an annual output of approximately 600,000,000 kwhr. Also,

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[2] "North of Scotland Hydroelectric Board Annual Report and Accounts, 1963," Her Majesty's Stationary Office, London, England, 1963.

[3] "Aluminium in the Highlands," Publication No. L. 34.2 m. British Aluminium Co., London, England, August, 1959.

three limited public supply schemes had a total capacity of 118,000 kw. They were Grampian Scheme (1922), Lanarkshire Hydro-Electric Scheme (1924), and Galloway Scheme (1929).

A committee was established in 1941 under the late Lord Cooper to look into future hydroelectric developments in Scotland. The Hydro-Electric Development (Scotland) Act was passed through Parliament in 1943 by the wartime Coalition Government and was piloted by the then Secretary of State for Scotland, Thomas Johnston. The Act was a direct result of the Cooper Report[4] published in 1942. Under the new Act a public body was established, The North of Scotland Hydro-Electric Board (NSEB), and was entrusted with the primary duty of development of water power in the Highlands. It is also responsible for distribution of power over a major part of Scotland together with numerous isles, a total area of approximately 22,000 sq miles. Subsequent legislation increased the Board's power and duties. The Electricity Act of 1947, which nationalized the electricity supply industry, left the Board as it is with an added responsibility of nearly 100,000 potential rural consumers.

TABLE 3.—STAGE REACHED IN HYDROELECTRIC PROGRAM OF NSEB

Schemes	Capacity, in kilowatts			Average Output, in million units per year		
	1961	1962	1963	1961	1962	1963
In operation	884,512	957,662	1,046,708	2,471.4	2,690.4	2,911
At construction stage	562,546	489,396	400,000	892	673	450
Under promotion	578,800	641,800	98,000	1,724	1,839	313

TABLE 4.—DISTRIBUTION OF CAPITAL EXPENDITURE OF NSEB TO THE END OF 1961, 1962, AND 1963

Items	Capital Expenditures, in pounds sterling		
	1961	1962	1963
Hydroelectric schemes	155,756,000	165,100,000	172,913,000
Steam and diesel power stations	5,544,000	5,795,000	7,857,000
Transmission lines	19,042,000	20,947,000	22,995,000
Distribution	45,575,000	48,864,000	53,074,000
Miscellaneous	2,051,000	2,429,000	2,828,000
Total	227,968,000	243,135,000	259,667,000

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[4] "Report of the Committee on Hydro-Electric Development in Scotland," Command Paper 6406, Her Majesty's Stationary Office, London, England, 1943.

In 1944, a map survey indicated that 6,300,000,000 kwhr can be generated from the Scottish Highlands. Undoubtedly, a closer estimation will increase the potential resources greatly and the writer believes that the final value may be as high as 10,000,000,000 kwhr per yr.

The first few years of the Board's existence consisted of hectic periods of surveying, preparation, and construction of schemes. Finally, in December, 1948, the first hydroelectric power station built by the NSEB was ceremonially opened at Falls of Morar in Inverness-shire with the prophetic words "Gun tigeadh Solus agus Neart an dealain dhionnsuich gach crout," which when translated means "Let electric light and power come to the crofts."

The Board's first large undertaking was the Sloy scheme where work began in 1945. At present (as of 1965) as many as 60 dams are in existence and, consequently, the average output has increased over the years to approximately 2,911,000,000 units per yr—the greatest single increase being 1950 to 1951 when the units generated improved from 322,000,000 to 522,000,000. Tables 3 and 4 show the increase in power generation and the total expenditure for various purposes to the end of 1961, 1962, and 1963, respectively.

FISH PASSES

Fishing plays an important part in the economy of the Scottish Highlands both as an industry and as a major tourist attraction. Under the 1943 Act, the Board has "to have regard to the desirability of avoiding as far as possible injuries to fisheries and to the stock of fish in any waters." Because the dams prove to be a serious obstacle for migration of anadromus species to spawn, fish passes must be provided. Large sums of money as well as time have been spent in developing better and simpler fish passes.

At Pitlochry (Fig. 2) simple overfall fish passes have been provided. In the foreground is the power station tailrace and the tailrace screen. A glass window enables one to see the fish swimming with ease; and it arouses great interest among the tourists. An electronic counter developed by the NSEB can record the number and size of fish, the time of the day, whether swimming up or down, and can even photograph individual fish automatically for identification. Recorded statistics can be seen in the annual reports of the Board.[2]

In more recent projects, however, Borland fish locks have been used as they proved to be more economical and beneficial to fish because less effort is needed for the ascent. The Borland fish lock was developed by the late Joseph Borland and was successfully used first at Leixlip in Ireland. The principle is simple. Once fish enter the chamber, A in Fig. 3, with the entrance at the tailrace level, B, the sluice gate is shut. Then the chamber is flooded in one operation and fish come out at the top, C. For high dams, two chambers may be used interconnected by a sloping shaft. Orrin Dam in Ross-shire (Fig. 4) has four different shafts because of the variation in the reservoir water level that can be as much as 80 ft. The NSEB has also perfected electric impulse screens which are as effective as mechanical ones but offer less resistance to the flow of water.

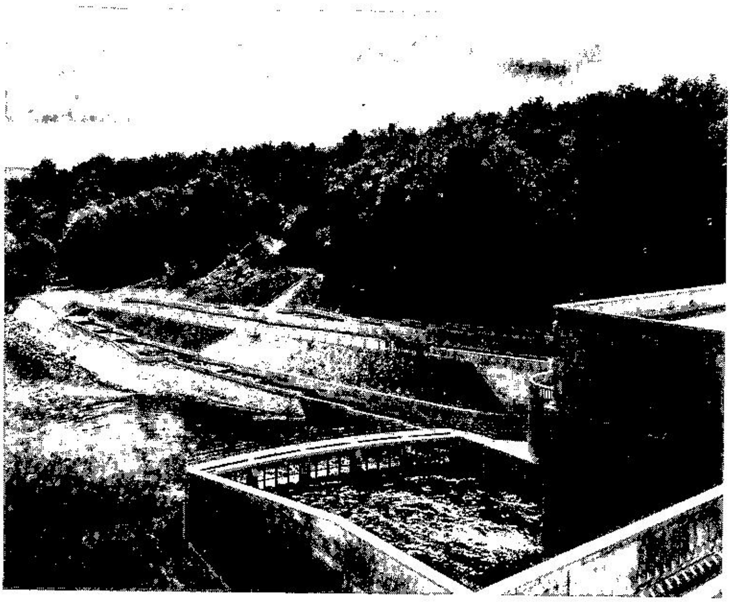

FIG. 2.—FISH PASS AT PITLOCHRY DAM AND POWER STATION

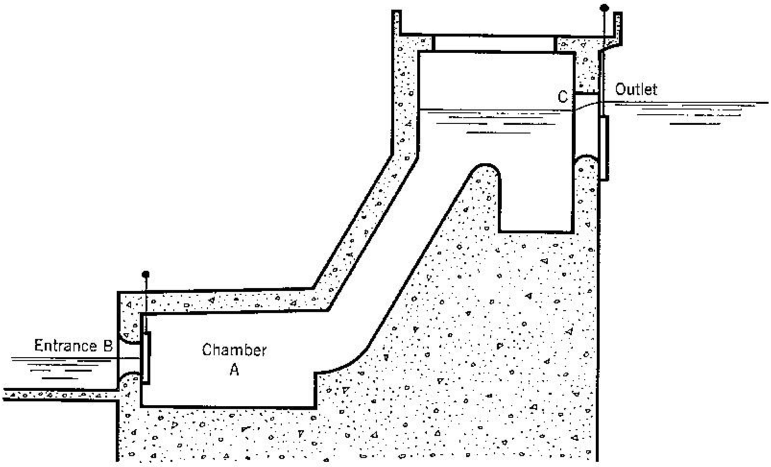

FIG. 3.—BORLAND FISH PASS

The three most interesting projects handled by the NSEB are briefly described herein.

GLEN SHIRA PROJECT

The scheme was designed to use a total of 1,098 ft in two stages. The upper stage which creates the main storage reservoir uses a head of 138 ft and the lower stage develops a fall of 960 ft. The project has a direct catchment area of 4.5 sq miles and drains another 8.75 sq miles of deverted catchments by tunnels and aqueducts. The average annual rainfall for the catchment area is nearly 105 in.

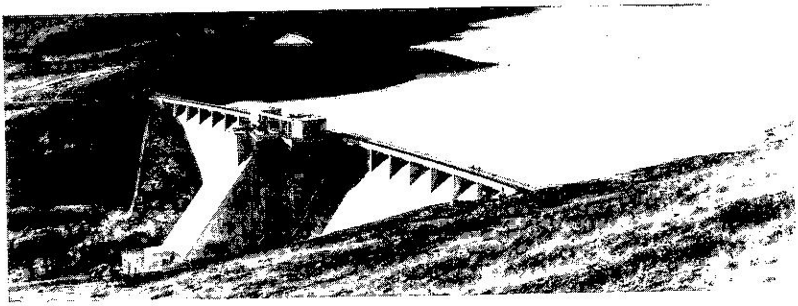

FIG. 4.—ORRIN DAM—THE SPILLWAY AND EMBANKMENT DAMS FROM THE NORTH BANK

FIG. 5.—GLEN SHIRA PROJECT—MAIN AND THE LOWER DAMS

The scheme consists of a main dam (Fig. 5) 133 ft above the river bed (148 ft above foundation level) on the upper reaches of the river Glen Shira. The round head buttressed dam is approximately 2,380 ft long. The main reservoir has an effective storage capacity of 750,000,000 cu ft. The dam has 37 buttresses on 50-ft centers that are separated by 5-ft contraction plugs.

The round head buttressed type proved to be the most economical for the site conditions. The dam has a volume of 260,000 cu yd of concrete that is estimated to be 50,000 cu yd less than a corresponding gravity dam.

The lower dam consists of a concrete gravity section (58 ft high and 477 ft long) and a 53-ft high earth-fill nonoverflow section[5] nearly 629 ft long. The reservoir has an effective storage capacity of 55,000,000 cu ft that represents approximately 1,000,000 units of electricity in reserve.

The most interesting aspect of the scheme is the relationship between its two reservoirs. The smaller lower reservoir has a storage capacity of approximately 7% of the total storage although it has a lion's share of the total catchment area, i.e., 38%. When the demand for power is less and output from the lower station is unnecessary, water is pumped from the lower to the upper reservoir—a height of nearly 130 ft—to be stored in reserve for peak period power generation by a pump in the upper station. The centrifugal pump is mounted on the same shaft as the turbine and motor/generator. When pumping is not needed, the pump is uncoupled thus allowing the turbo-alternator to work at full efficiency.

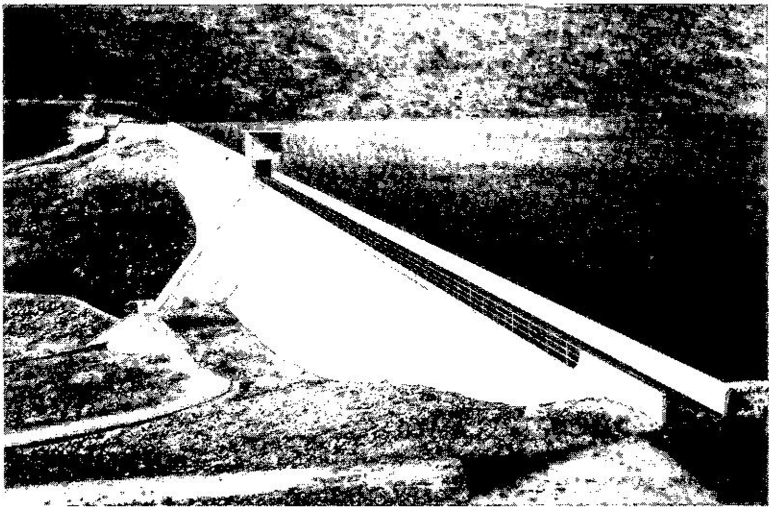

FIG. 6.—ALLT-NA-LAIRIGE PRESTRESSED CONCRETE DAM

The power station of the scheme at Clachan is the first major underground station built in Great Britain. It used the 960-ft gross head available from the lower stage. The full-load demand of the turbine requires 630 cfs, which is conveyed through the main tunnel with an average diameter of 10 ft and pressure shaft works—a total length of nearly 4.5 miles. The Francis turbine develops 56,000 bhp at 428 rpm and generates 40 mw of power.

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[5] Paton, John, "The Glen Shira Hydro-Electric Project," Proceedings Paper No. 6152, Institution of Civ. Engrs., London, England, September, 1956, pp. 593-632.

The total estimated cost of the project was £7,000,000 ($19,600,000) which included generating plant and transmission lines. Complete descriptions of the scheme can be found in the papers by Paton[5] and J. C. Beverly.[6]

ALLT-NA-LAIRIGE SCHEME

Although Allt-Na-Lairige is not among the largest projects of the NSEB, it deserves mention as the first prestressed concrete dam (Fig. 6) built in Europe (1956). Situated in Argyllshire, west of Scotland, the dam is 73 ft high and 1,395 ft long, 966 ft of its length being prestressed.[7] The scheme has a total catchment area of 5.3 sq miles. Nearly 3.2 sq miles drain direct to the reservoir and water from the rest is diverted by means of aqueducts and shafts to the reservoir and tunnel. The storage capacity of the reservoir is 130,000,000 cu ft and average annual rainfall over the catchment area is estimated to be 125 in. per year.

Initially, a 64-ft high gravity dam was proposed, but it resulted in a limited storage of only 7.5% of the average annual run-off. Alteration of height meant a substantial increment in the unit cost of power generation. Hence, a prestressed concrete dam was used, and the storage was increased to 10%. Because the tendering stage was over, necessary adjustments were made for the new design with the firm that submitted the best bid for the gravity dam. The volume of concrete saved in the prestressed sections was near 40%. The central and end blocks were designed as ordinary gravity sections.

Each prestressing tendon comprised 28 high tension steel bars, 1-1/8 in. in diameter. The tendons were placed 21 ft apart along the length of the dam. A typical cross section through the anchorage is shown in Fig. 7. Concreting was done in block lengths of 42 ft, and with two tendons per block. A load of 1,176 tons per tendon was applied that resulted in 56 tons of prestressing per linear foot of the dam. The dam was designed for a maximum tension of 50 psi, with practically no tension on the upstream side and top 21 ft of the downstream side.

The capacity of the generation plant is 6,000 kw and the average annual output is 20,000,000 units.

CRUACHAN SCHEME

The Cruachan pumped storage scheme is a part of Awe Project which is divided into three parts, Cruachan, Inverawe, and Nant. The Awe Project has a total catchment area of 324 sq miles with an average rainfall of 91 in.[8]

The Cruachan Project is one of the largest pumped storage schemes in the world, the largest being Vianden[9] in Luxembourg. The general layout of the scheme is shown in Fig. 8. The scheme consists of a 150-ft high massive buttress dam (Fig. 9) with a central gravity section. The reservoir thus

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[6] Beverley, J. C., "Loch Sloy Power Scheme of the North of Scotland Hydroelectric Board," English Electric Journal, English Electric Co. Ltd., Stafford, England, Vol. XII, No. 3, June, 1951, pp. 3-20.

[7] Banks, James A., "Allt-Na-Lairige Prestressed Concrete Dam," Proceedings Paper No. 6194, Institution of Civ. Engrs., London, England, March, 1957, pp. 409-444.

[8] "The Awe Scheme," Water Power, London, England, Vol. 16, No. 5, May, 1964.

[9] "Vianden," Water Power, London, England, Vol. 16, No. 7, July, 1964.

formed will have a total storage capacity of 399,000,000 cu ft in which natural storage will play a minor part. The central gravity section will have two penstocks for the intake. There are six buttresses to the east of the section and five to the west, spaced on 50-ft centers. The dam has a 128-ft long spillway having a capacity of 3,840 cfs.

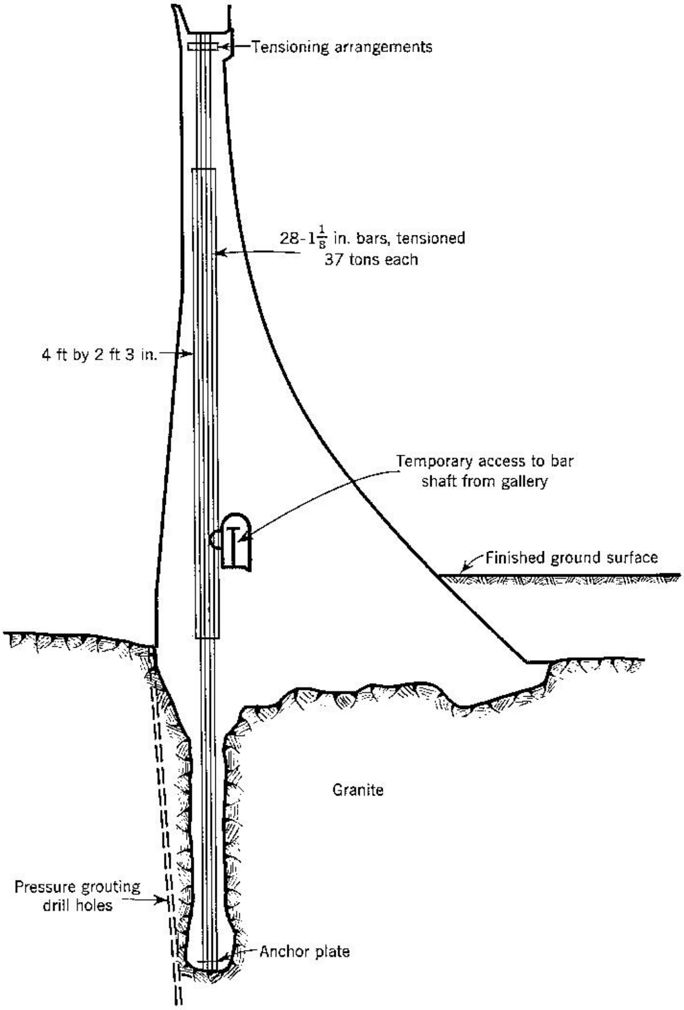
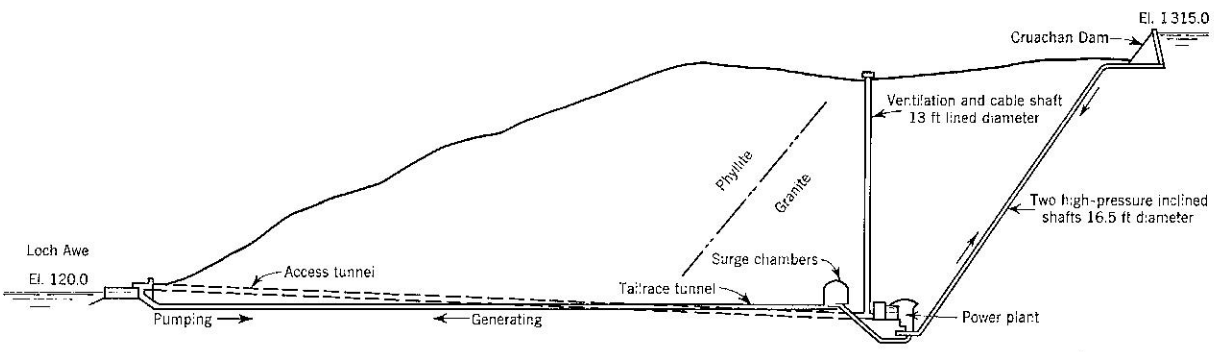
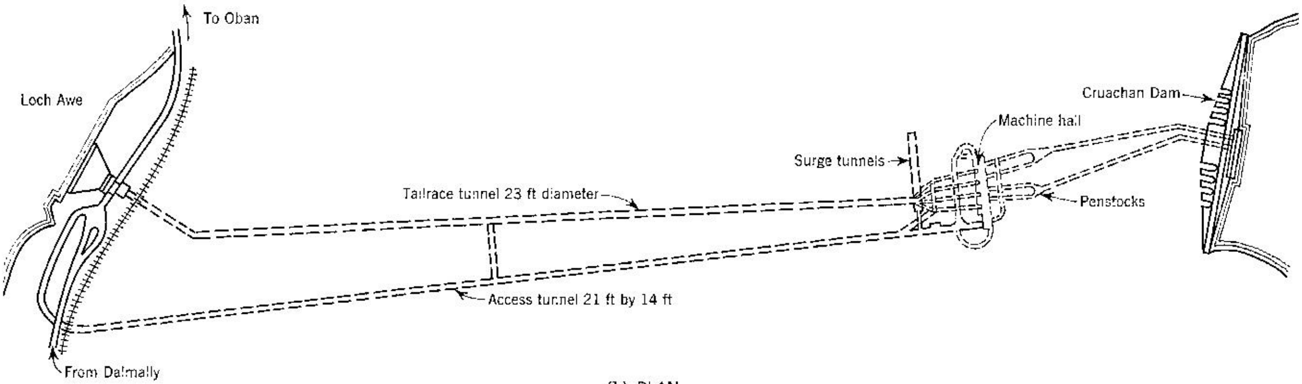


FIG. 7.—TYPICAL CROSS SECTION OF THE PRESTRESSED SECTION OF THE ALLTNA-LAIRIGE DAM

Nine miles of tunnel (generally 10 ft by 8 ft and 8 ft-6 in. by 7 ft-6 in. in section) and three miles of pipe line with diameters to 30 in. have been used



(a) SECTION



(b) PLAN

FIG. 8.—GENERAL LAYOUT OF THE CRUACHAN SCHEME

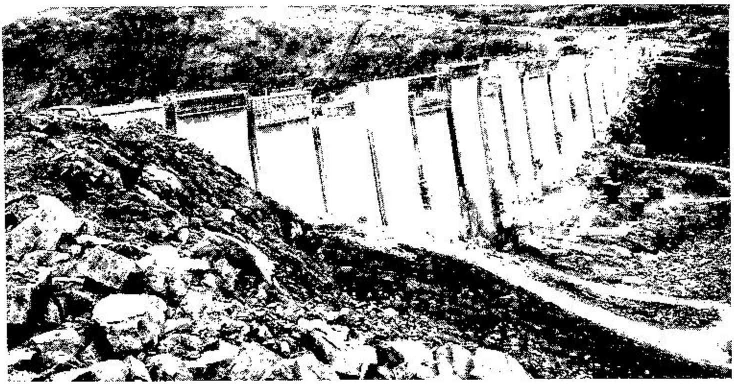


FIG. 9.—UPSTREAM FACE OF THE CRUACHAN DAM—UNDER CONSTRUCTION

FIG. 10.—CRUACHAN UNDERGROUND POWER STATION—UNDER CONSTRUCTION

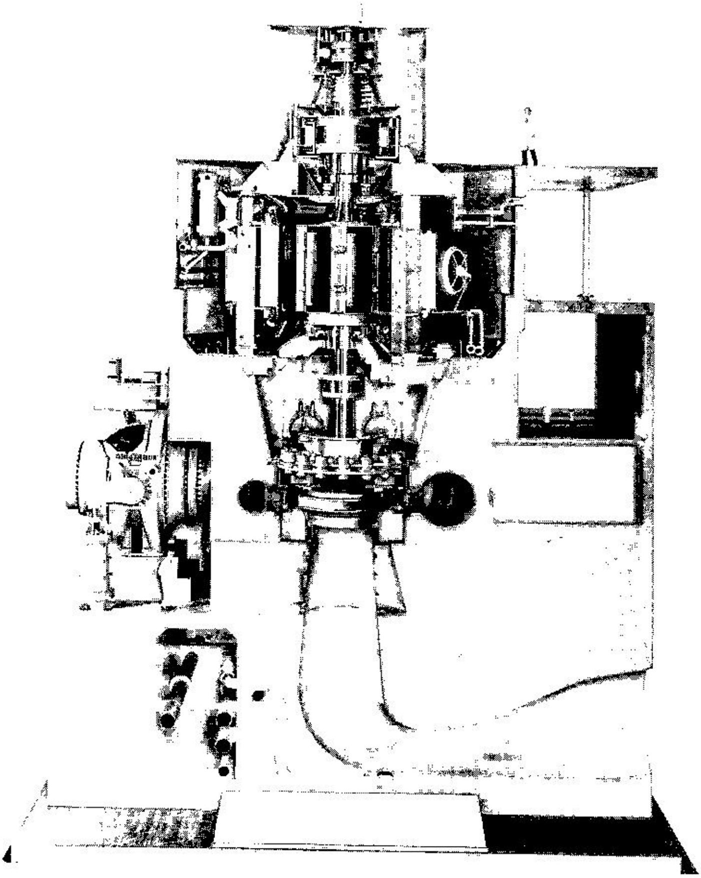


FIG. 11—MODEL OF TURBINE USED AT CRUACHAN

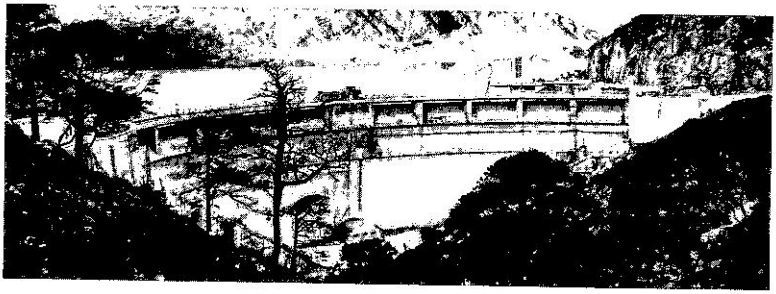


FIG. 12—THE FIRST THIN ARCH CUPOLA DAM OF U.K. AT MONAR

to bring water to the reservoir catchment. The aqueduct tunnels are unlined except for concrete culverts.

The gross head for the scheme is 1,240 ft and two inclined shafts lead to the completely underground power station (Fig. 10) having four 100 mw reversible vertical Francis pump turbines. Nearly 200,000 tons of rock had to be excavated for the machine hall whose dimensions are 300 ft by 77 ft by 120 ft high. The capital cost is estimated[10] at £34 per kw and operation and maintenance cost at £0.2 per kw sent out per year. It compares favorably against a thermal plant that would have had a capital cost of 45 per kw[10] and operation and maintenance cost of £0.9 per kw sent out per year.

The most interesting features of the plant are the high speed and large submergence possible in an underground plant—the spiral casing centers being at a depth of 150 ft below the minimum water level of Loch Awe. When all four units are in operation, the rated output for each will be 100 mw under a gross head of 1,142 ft and 0.9 power factor, having 142,000 hp. The units can absorb 110 mw while pumping at 0.98 power factor.

The pump turbines (Fig. 11) are to be spaced on 46-ft centers and can pump 900 cfs at the maximum head of 1,204 ft and 1,100 cfs at the minimum head of 1,103 ft. Two, 142,000 hp, 1,142-ft head turbines and two 111,111 kva 16,000 v 50 cycles per sec at 500 rpm alternators will be installed. The other two units will have a speed of 500 rpm.

The work on the scheme began in mid-1962 and is expected to be completed by 1966.

CONCLUSIONS

In 21 yr, from the first inception of the North of Scotland Hydro-Electric Board, nearly 60 dams have been built. At the end of 1963, the total generating capacity was 1,046,708 kw including 400,000 kw under construction and another 98,000 kw being designed. The NSEB has approximately 270 circuit miles of 275,000 v and 2,000 circuit miles of 132,000 v overhead transmission lines, and 18,000 miles of distribution lines capacity of which nearly 3,000 miles is underground. In 1948, 7% of the farms and only 1% of the crofts were connected to the mains but now (1965) the value for both is 85.8%.

Operating heads developed varies from a mere 18 ft for Kaplan turbines at Morar, to 1,362 ft for Pelton turbines at Finlairg (Lawers). A Francis turbine has been used at 200-ft range and the reversible pump turbine at Cruachan is one of the highest of its type in the world.

Various types of dams have been constructed, including the prestressed concrete dam at Allt-Na-Lairige, the first thin arch cupola dam in Great Britain at Monar (Fig. 12), the rock-fill at Quoich, and the massive buttress at Sloy. Because of the small catchment areas available for most schemes, a system of tunnels and aqueducts has been used to collect water from a wider area.

The contribution of the NSEB to the economic prosperity of Scotland is indeterminable in terms of money. It has been estimated that 264 new in-

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[10] Allan, C. L. C., Warren, T. R., and Campbell, W. T., "Improved Pumped-Storage Schemes in Scotland," Paper No. 81, 14th Sectional Meeting, World Power Conf., Lausanne, Switzerland, September, 1964.

dustrial concerns employing some 74,000 people have been established because of availability of power at a reasonable cost. Another 9,000 people are employed at various construction projects of the NSEB. The decision to build power houses with Scottish stone instead of concrete has revived the stone industry. Four hundred miles of roadway have been built by the Board out of which nearly 100 miles have been handled over to the public authorities. It has resulted in a growing trade of "bed and breakfast" accommodation for the local people in areas that were once considered remote.

The NSEB has taken infinite care to preserve the Highland scene. The Aigas Dam was built higher up the Beauly river than was originally planned for the sole reason of not interfering with the picturesque outcrop of rock in midstream at Sugar Loaf. Wherever possible, pipelines have been laid underground and the surface lines are painted to match the surroundings along with screens of trees and bushes. Power stations built with Scottish stones not only look elegant but blend smoothly with the local landscape. It was reported in the national press that when a bus-load of "dam beggars," from the International Congress on large Dams held at Edinburgh, first saw Kilmorack on the Beauly Gorge, they clapped their hands in admiration.

Summing up can best be done by quoting from the report[11] of the "Select Committee on Nationalised Industries (Report and Accounts)" which in 1957 stated that "In the 14 years of its existence the North of Scotland Hydro-Electric Board has impressively justified the faith of its progenitors."

ACKNOWLEDGMENTS

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[11] "Report from the Select Committee, with the Proceedings of the Committee, Minutes of Evidences and Appendices," Select Committee on Nationalized Industries, Her Majesty's Stationary Office, London, England, 1957.

KEY WORDS: dams; hydroelectric power generation; power; power plants; reservoirs; Scotland

ABSTRACT: The growth of hydroelectric power in Scotland, available for public supply schemes from a mere 188,000 kw in 1942, to over 1,046,708 kw at the end of 1963, is outlined. During the same period, the North of Scotland Hydro-Electric Board has built 60 dams and spent some £ 259,667,000 in the process. The interesting aspects of certain schemes have been described together with the efforts made to maintain fishing and landscape. The contributions of water power to the economic developments of the Scottish Highlands have been examined.

REFERENCE: Biswas, Asit K., "Hydroelectric Developments in the Scottish Highlands," Journal of the Power Division, ASCE, Vol. 91, No. PO1, Proc. Paper 4318, May, 1965, pp. 23-38.